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Critical Role of Water for Energy Transitions Technologies: A Literature Review

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SUMMARY

This report summarizes the water inputs associated with four technologies playing diverse roles in energy transitions: hydrogen, solar photovoltaics (PV), wind, and batteries. Information in this report is drawn from multiple sources, including peer-reviewed literature, industry and international agency reports, EcoInvent life cycle inventory database, and subject matter expert (SME) consultations. Where possible, insights that characterized water requirements for specific stages of the technology development (e.g., operations, manufacturing, and mining) were prioritized over broader cradle-to-gate assessment values. Furthermore, both direct and indirect water requirements (i.e., associated with associated energy inputs) were considered in this literature review (Figure 0-1).

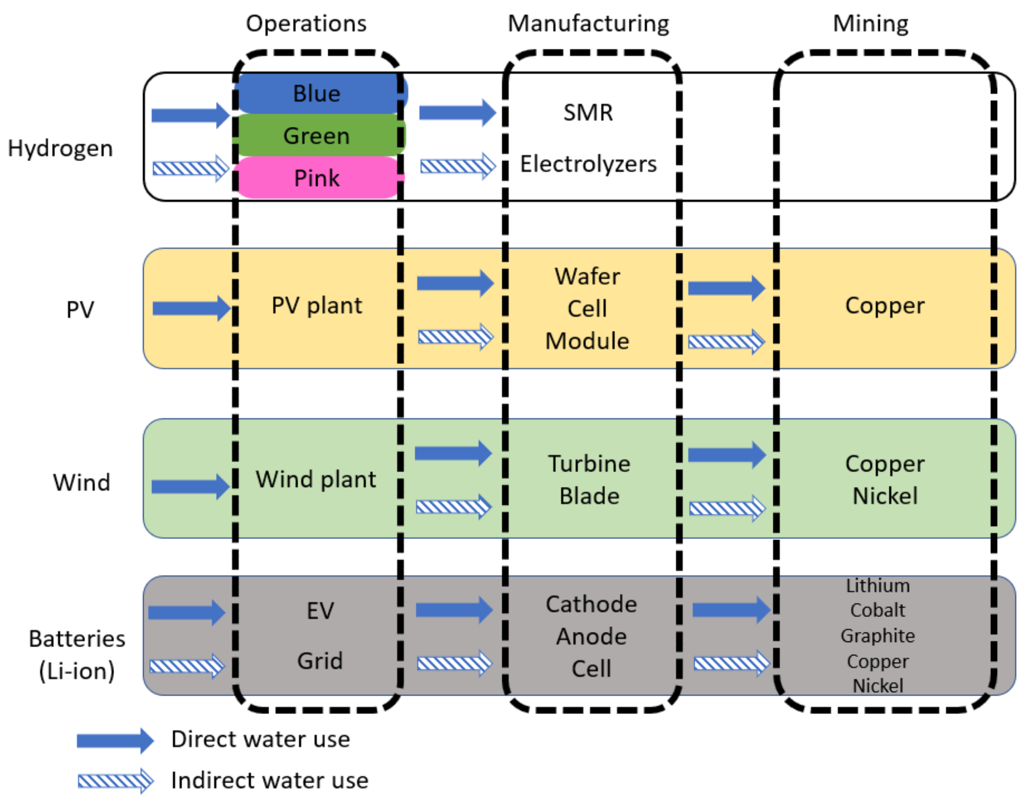

Figure 0-1 Water touchpoints explored for the operations, manufacturing, and mining activities for this report. Solid blue arrows indicate direct water use whereas hashed arrows indicate indirect water use that stems from electricity requirements. Neither PV nor wind have indirect water requirements for operations. The colors blue, green, and pink refer to different hydrogen production pathways.

Current literature generally indicates that of the four technologies, hydrogen will require the most water as a direct input during the operations stage, across the various production pathways and associated energy inputs (Figure 0-2). In contrast, the use of battery technologies only requires direct water inputs for grid-based operations and the estimates for direct water inputs for PV and wind are both consistently low. Indirect water requirements during operations is only relevant for battery and hydrogen technologies, both of which have energy requirements. Depending on the underlying energy source, water withdrawals supporting the energy inputs for battery and

hydrogen operations can range from 0 (for wind-based energy generation) to thousands of liters of water (for nuclear energy based generation).

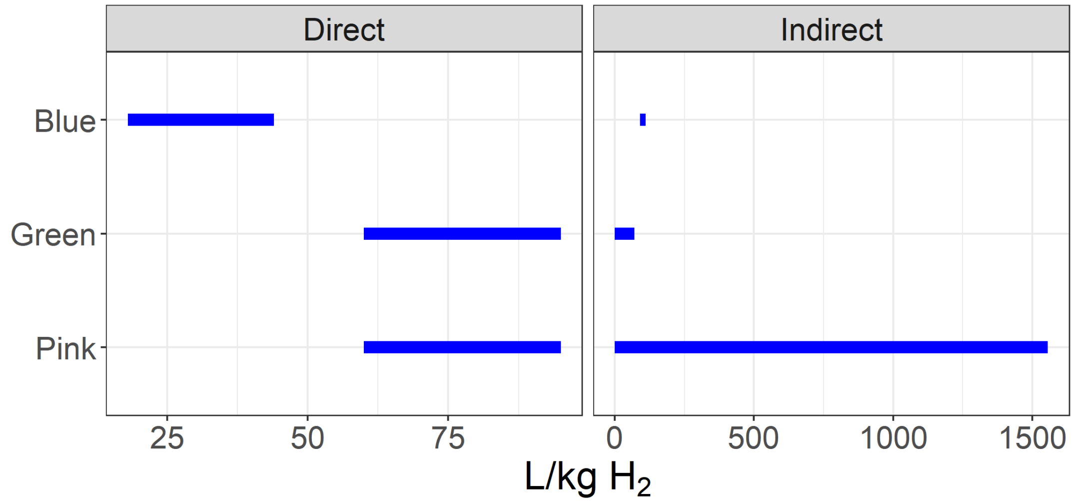

Figure 0-2 Direct and indirect water withdrawals for hydrogen production. The different colors indicate the respective technologies and energy sources: Blue = steam methane reformer with natural gas-based inputs, Green = electrolyser with wind or solar energy inputs, and Pink = electrolyser with nuclear energy inputs.

Manufacturing details are relatively sparse for all four technologies, with SMEs indicating that this information might be considered proprietary (for hydrogen) and not a relevant factor in decision-making (for batteries). Water-related manufacturing requirements for wind were limited as well, although initial evaluations indicate most of the water is not consumed. PV-related manufacturing assessments indicate that most of the water is required for polysilicon activities than for wafer, cell, or module-specific needs.

Finally, water consumption requirements for five critical minerals indicated that cobalt requires the most water cradle-to-gate than the other four minerals (Figure 0-3). Although lithium did not require as much water as cobalt, lithium processing is mostly concentrated in water stressed

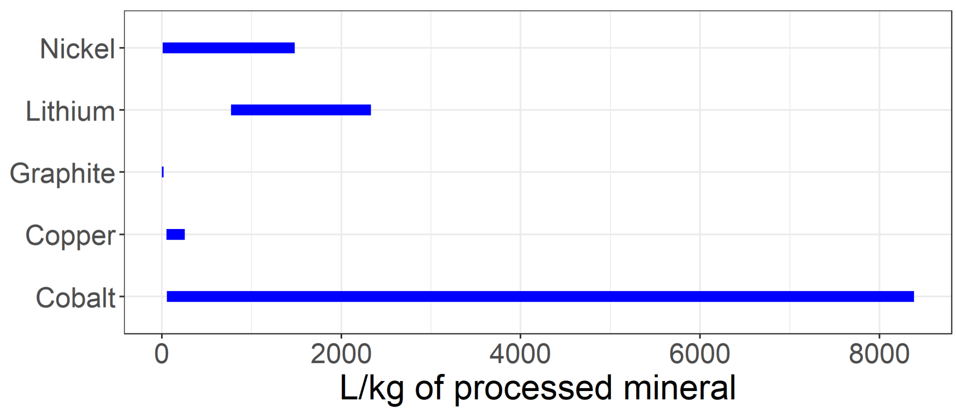

Figure 0-3 Cradle-to-gate water consumption for mining activities. Range of values (minimum and maximum) reflect diverse requirements depending on the mineral source type and processing techniques.

regions. While lack of comprehensive data precludes direct comparisons, hard-rock sources tended to require more water than brine-based methods for mineral extraction and processing.

Resource scarcity concerns have led some of the energy technology sectors to pursue water adaptation practices. These range from using different sources of water to cooling related improvements (Table 0-1). Unfortunately, specific numbers of reductions are captured in few industry-specific reports and thus, it is hard to ascertain how widespread these adaptations are across regions within each sector.

Table 0-1 Strategies being pursued for water scarcity and conservation-related adaptations within each of the four energy technologies.

Sector	Adaptations
Hydrogen	Saline water sources Water-efficient cooling technologies Water reuse
Wind	-
PV	Water recycling Reduction of cross-contamination
Li-B	Water-efficient cooling technologies Streamlining cleaning activities
Mining	Water reuse Use of lower quality water Dry processing

It should be noted that lack of consistency in functional units analyzed and lack of statistically representative water data are significant limitations of this study. Thus, the presented values should be viewed more as relative magnitudes versus absolute numbers. Furthermore, only certain activities associated with the four energy technologies were considered for this review (e.g., certain production pathways for hydrogen). Future work could expand this scope to consider additional activities that influence water for emerging energy technologies, such as recycling, time variant nature of water resources, water quality nuances, community acceptance, and region-specific priorities.

ACRONYMS

CSP concentrated solar power

Co cobalt

Cu copper

EV electric vehicle

Gr graphite

GW gigawatt

H_2 hydrogen

kg kilogram

km kilometer

kWh kilowatt-hour

L liter

LCA life cycle assessment

LCI life cycle inventory

Li lithium

Li_2CO_3 lithium carbonate

Li-B lithium-ion battery

m^2 square meter

m^3 cubic meter

MJ megajoule

MW megawatt

MWh megawatt-hour

Ni nickel

NMC nickel manganese cobalt

PV photovoltaics

SME subject matter expert

SMR steam methane reformer

TDS total dissolved solids

1. INTRODUCTION

1.1. Energy Transitions

The global energy sector is currently undergoing rapid transitions, with many looking to shift the way that energy is generated, stored, and carried [1]. Although energy transitions have occurred in the past (e.g., when some nations shifted from fuelwood to oil-based energy generation; [2, 3, 4]), the scale of current transitions is unprecedented with respect to the number of nations that are concurrently engaged in these transitions. As part of these energy transitions, nations are pursuing multiple activities, from energy efficiency practices to investing in emerging technologies, which include increasing the use of renewable sources of energy (e.g., wind and solar), leveraging hydrogen, electrifying mobility, and pursuing carbon capture and sequestrations [5] (Figure 1-1).

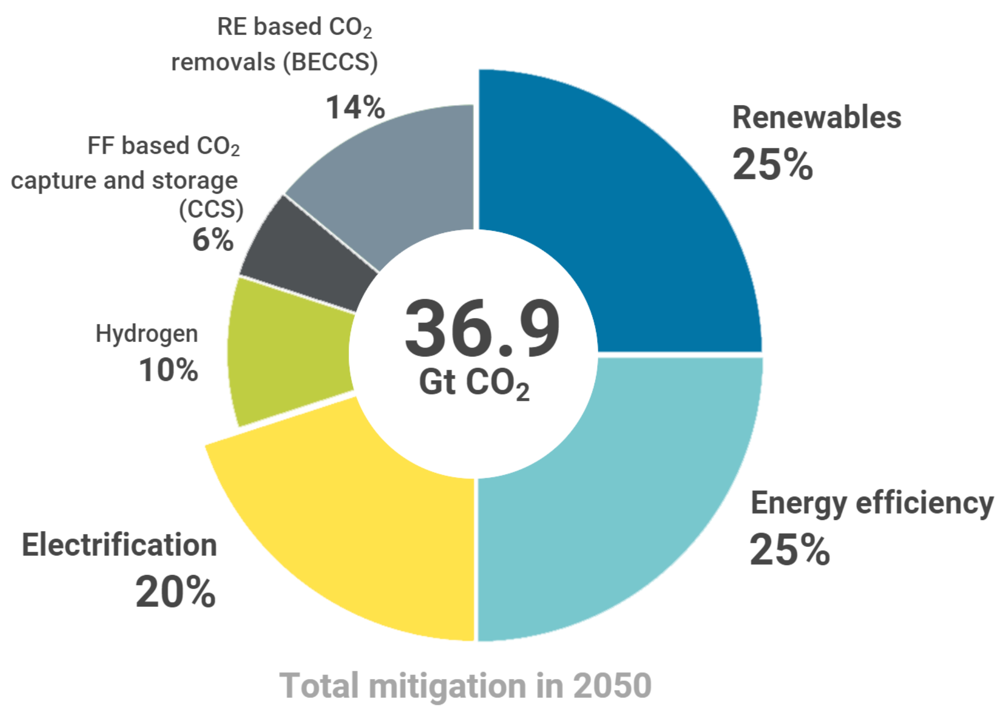

Figure 1-1 Energy transition strategies span energy efficiency and renewable generation to hydrogen production and carbon management activities. Source: [6]

Motivations for adopting these emerging technologies vary, including reducing foreign dependence and climate-related objectives aiming to achieve net-zero emissions by 2050 [7, 8]. Although some regional differences are expected to emerge with respect to roll-outs [9], the general expectation is that the adoption of these energy transitions will be accelerated across the globe as the underlying technologies mature and the levelized cost of electricity decreases. Although scarcity of resources has spurred technological innovations in the energy sector in the past [3], the scale of current transitions has raised concerns about supply chain reliability for many, especially given the limited availability of natural resources and increased demands for energy from climate change [10, 1, 11].

1.2. Water-Energy Nexus

One resource that has received relatively little attention to date in the context of energy transitions, is water. Water and energy reflect two codependent systems; water influences all phases of energy production, including fossil fuel generation to biofuels and hydropower operations while energy is required to collect, treat, and distribute water [12]. Energy inputs for water, such as groundwater pumping and desalination activities, can amount to as much as 9-12% of total energy usage in some regions, such as the Middle East and Northern Africa [13]. For the purposes of this report, we focus primarily on water for energy, including possible energy requirements to treat water to meet energy demands.

Lowering the carbon footprint of energy production does not necessarily mean that the water footprint is also lowered [14]. In fact, World Energy Outlooks project that the inter-dependencies between the two resources are expected to intensify in the coming decades as the water needs for the energy sector rise [15, 14]. Unfortunately, water availability continues to be a concern across many regions of the world, due to a combination of increasing use across sectors as well as changing precipitation patterns from climate change [15]. Research into water for energy production dates back decades, with many focused on quantifying the footprints (i.e., amount of water needed) using a range of techniques at different scales of analysis [15, 16, 17]. Generally, the focus for water needs for energy productions has been on certain pathways that are deemed to be most dependent on direct inputs of water - thermoelectric power plants, hydropower, and biofuels [18, 19, 20, 21].

Although water scarcity has raised concerns about possible limitations to energy production [22], limited attention has been given to the critical role of water for facilitating emerging technologies associated with the energy transitions [23]. This is a significant oversight since there are already early signs that water can serve as a limiting factor for energy transition technology roll-outs (e.g., [24]). To develop a more comprehensive understanding of the role of water for emerging energy technologies, we conducted a literature review to synthesize the latest insights regarding possible touchpoints to water for select energy transition technologies. The scope of this literature is detailed in the following section (Section 2) and associated findings are summarized in Section 3. We then conclude with a summary of reflections on the findings, including limitations of this work and opportunities for future research (Section 4). As described in the following sections, there is a general paucity of water-related data in the context of energy transitions. Thus, more attention is needed for this topic, especially given the increasing tensions on water resources from climate change and other regional conflict [25, 26, 27].

2. SCOPE

Four energy transition-related technologies were selected for this report: hydrogen, solar photovoltaics (PV), wind, and batteries (Figure 2-1). These technologies were selected based on the potential for touchpoints to water, through a combination of global interest and amount of water required per unit energy. For example, although concentrated solar power (CSP) has a larger lifetime water requirement (approx. 100x) than solar photovoltaics (PV) [28], PV installations are occurring at a much larger scale than CSP-related installations [29]. The selected four technologies play diverse roles in energy transitions, from serving as an energy carrier (hydrogen) to electricity generation (PV and wind) and energy storage (batteries).

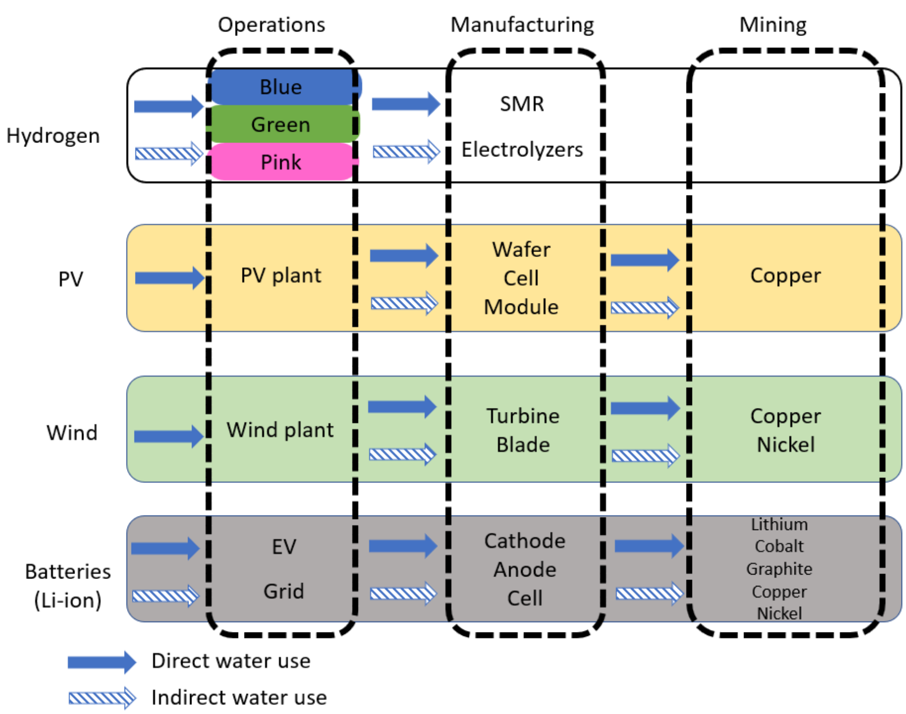

Figure 2-1 Water touchpoints explored for the operations, manufacturing, and mining activities for this report. Solid blue arrows indicate direct water use whereas hashed arrows indicate indirect water use from electricity requirements. Neither PV nor wind have indirect water requirements for operations.

For each technology, we focus on water inputs associated with operations of that technology as well as associated manufacturing and mining-related inputs. Information in this report is drawn from multiple sources, including peer-reviewed literature, industry and international agency reports, EcoInvent life cycle inventory (LCI) database (version 3.9.1) [30, 31], and subject matter expert (SME) consultations. Insights (from the literature or SMEs) that characterized water requirements for specific stages of the technologies were prioritized in this summary. However, there were instances when such numbers were not available within the dataset. For these cases, numbers from the LCI database, which collects life cycle assessment (LCA) values for a range of boundary conditions were used. Two common boundary conditions within the LCI are cradle-to-grave and cradle-to-gate. Cradle-to-grave assessments include material extraction through the final disposal or treatment and includes processes such as transportation,

manufacturing, construction, and operations [30, 31]. Cradle-to-gate assessments, on the other hand, only consider material extraction, transport, manufacturing, ending at the consumer or production facility [30, 31]. Other nuances of values within LCI database include geographic region that an assessment took place and the different methods use to calculate generate LCAs. For this report, water consumption values sourced from the LCI (for wind, PV, batteries, and minerals) were derived using the ReCiPe method [32].

To help breakdown details from LCAs, the literature insights are organized into three parent categories: operations, manufacturing, and mining (Figure 2-1). Operations refer to the production of hydrogen, electricity generation activities (for wind and PV), and use of batteries (for electric vehicles (EVs) and grid). For this analysis, manufacturing-related activities are limited to first-order dependencies for the technology production, i.e., the technology needed to produce the energy of interest. For example, hydrogen production requires electrolysers and steam methane reformers (SMRs), PV requires solar panels, wind production requires turbines, and batteries require the batteries themselves. Outside of cradle-to-gate summaries, second-order dependencies (i.e., the water footprint associated with electricity consumption during manufacturing or the water needed to manufacture the equipment that is involved with manufacturing the technologies) are not considered in this review. Mining was added, in part, given the increasing concerns about the sustainability of these activities in support of low-carbon energy transitions [33]. For this report, the focus is restricted to five minerals that were identified as critical for energy transitions [34]: lithium, copper, cobalt, nickel, and graphite. The selection of these minerals was driven by the volume of materials needed for energy transitions (versus specific water footprint details).

Where possible, numbers for both water withdrawals (i.e., total amount of water used for a specific purpose) as well as water consumption (i.e., amount of water lost to evaporation or other losses) are provided. In addition, across these categories, both direct water inputs as well as indirect water inputs (i.e., stemming from energy requirements) are captured (Figure 2-1). The indirect water use for operations depends on the source of the energy [35]. To support conversion of electricity values into water equivalents, global median values for natural gas (2.3 liters per kiloWatt-hour (L/kWh)) and nuclear nuclear (26.7 L/kWh) are used in this report [36].

This literature review does not consider downstream dependencies outside of the immediate technologies (e.g., storage of hydrogen or distribution of electricity). Additional details about each technology, including global interests are provided in the following subsections. Given their use in multiple technologies, mining details are summarized in their own subsection.

3. WATER FOR ENERGY TECHNOLOGIES

3.1. Hydrogen

3.1.1. Background

Hydrogen is a nontoxic gas at room temperature (chemical form: H_2) that can be condensed into a liquid at low temperatures (at approximately -253 °C) [37]. Over 30 countries around the world (including US, India, China, Australia, and Germany) have started to develop strategies around hydrogen [38, 39]. The global interest in hydrogen is driven by its ability to: 1) help decarbonize hard to electrify, energy-intensive industrial activities (e.g., steel, cement, and chemical production); 2) capture emissions from petrochemical refining and other energy generation sectors; and 3) serve as fuel for long-haul transportation (including through blending) [40, 37, 41]. Hydrogen is already being used for some oil refining and the production of ammonia, methanol, and steel today. But there is significant interest stemming from larger-scale use in the other sectors. Current future projections estimate that hydrogen demand can reach 70+ exajoules [39].

Since the production of hydrogen requires significant energy inputs, hydrogen is more aptly described as an energy carrier that can serve as a low-carbon alternative to fossil fuels. One kilogram of hydrogen contains the same energy content as one gallon of gasoline [42]. However, the low-carbon (or 'clean hydrogen') label only applies to hydrogen generated with certain energy sources and production pathways, namely those that use renewable energy, nuclear energy, and natural gas with carbon capture/storage (Figure 3-1). For the purposes of this literature review, we only focus on the water touchpoints of these low-carbon energy pathways, hereafter referred to with their associated colors: blue hydrogen, green hydrogen, and pink hydrogen [43][1]; turquoise hydrogen is excluded from this review due to lack of available information about water for methane pyrolysis. Accordingly, SMR and electrolysis techniques are the focus of this analysis, since they are involved in the generation of hydrogen across the selected (i.e., blue, green, and pink) pathways [37, 44].

3.1.2. Hydrogen Production

Water requirements are relatively high during the operations of a hydrogen production plant (95%) compared to those required for construction and decommissioning activities [45]. Given the significant resource inputs required to produce hydrogen, life cycle assessments typically include energy inputs for hydrogen (e.g., [45]). Thus, water for hydrogen during operations is distinguished into both direct water and indirect water inputs, with the latter focusing on water requirements for associated energy inputs.

The direct water needs for hydrogen production plant operations are dependent on the specific technique (e.g., SMR versus electrolysis) used to produce hydrogen, quality of the initial water source, cooling technology, and recovery processes associated with waste management. For

[1] This website was taken down recently, but the original content was accessed through the Wayback Machine archive.

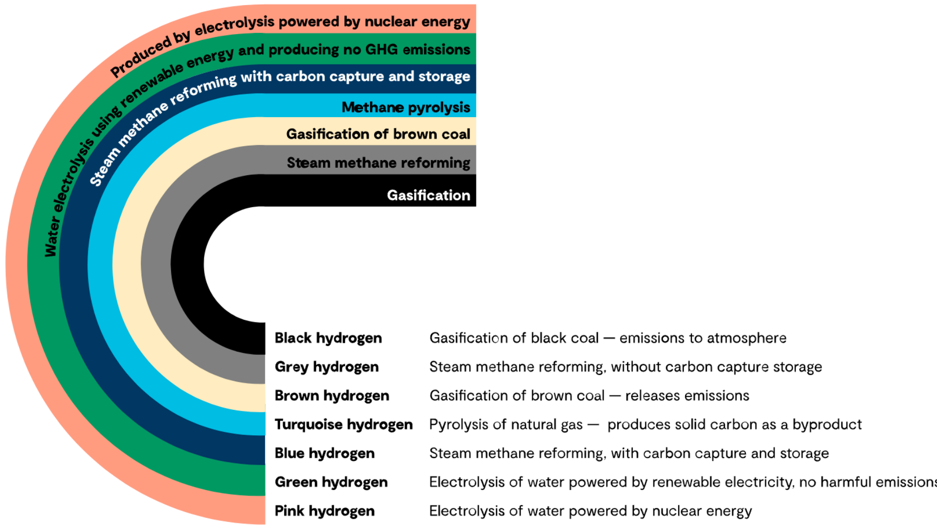

Figure 3-1 Hydrogen production pathways are often referred to using colors, based on the specific technology used (e.g., steam methane reforming, pyrolysis, or electrolysis) as well as associated energy and carbon activities. Source: [43]

example, production of blue hydrogen using evaporative cooling methods is estimated to require 18-44 liters of water (L of water) per kilogram of hydrogen (kg H_2), with 4.5 L and 4 L of water required for feedstock (i.e., demineralized) and carbon management activities, respectively (Table 3-1). The remaining water represents reject water from the demineralization process as well as losses from evaporation [43]. In contrast, the production of green hydrogen using evaporative cooling has a higher total water requirement (60-95 L of water per kg H_2) due to significant cooling requirements of electrolysers (Table 3-1); approximately 30-40 L of the total water per kg H_2 and 10 L of water per kg H_2 is attributed to blowdown and evaporation losses, respectively. The stochiometric consumption is also greater for green hydrogen since all of the hydrogen is sourced from water (versus partially sourced from methane for blue hydrogen). See Table 3-1 for a summary of these numbers. For the purposes of this analysis, the production-specific water requirements for pink hydrogen are assumed to analogous to green hydrogen since both use electrolysis techniques.

The approximate differences between SMR and electrolysis-related water requirements also extend to water consumption-related activities, with estimates ranging on average from 11.7 L of water per kg H_2 for SMR to between 18-30.2 L of water per kg H_2 for electrolysis pathways [46, 47]. Although there are some water efficiency improvements observed with increasing sizes of electrolysers, the general breakdown of water is dominated by consumption activities (64%) with the remaining 36% of withdrawn water being returned [47].

The total water estimates increase by multiple orders of magnitude depending on the specific technologies used for electrolysis and cooling. For example, proton exchange membranes typically consume twice the amount of water as solid oxide electrolysis cells [48]. Similarly on the cooling side, once-through cooling requiring greater volumes of water overall while recirculating cooling experiencing greater consumption [35]. In recognition of possible water scarcity concerns, there has been increased interest in using non-traditional water sources (such as

seawater, brackish groundwater, produced water, and other wastewater sources) for hydrogen production [49]. Generally, the water requirements for hydrogen production increases from 2x to up to 12x when considering these alternate water sources [43] (Table 3-1).

Table 3-1 Water withdrawal requirements for gaseous hydrogen production using evaporative cooling and co-located energy generation. Values for blue hydrogen include those associated with carbon management activities while treatment of seawater and produced water assume use of reverse osmosis.

	Blue	Green	Pink	Source
Direct water input for hydrogen production plant (L/kg H_2)				
Freshwater	18-44	60-95	60-95	[43]
Seawater	45-110, up to 220	150-238, up to 475	150-238, up to 475	[43]
Produced water	36-88	120-190	120-190	[50]
Indirect water input for hydrogen production plant (L/kg H_2)				
Energy for SMR	100			[45, 36]
Energy for electrolysis		0-70	1556	[47, 36]
Energy for treating seawater	1.1	0-3.1	13.3	[43, 36]

Although more direct water is required for electrolysis than SMR activities, the overall water footprint of blue hydrogen and pink hydrogen (relative to green hydrogen) is higher due to indirect water inputs associated with energy inputs [51]. In particular, if energy generation to support hydrogen production is done onsite, then water requirements for the energy generation would add to the total amount of water required to produce hydrogen. Generally, nuclear power production requires 26,690 liters per megawatt-hour of electricity (L per MWh) while natural gas production requires 2,255 L per MWh during power plant operations (median values from [36]). These values are much greater than the median values of 6.1 and 0 L per kWh required for PV and wind plant operations respectively (see Tables 3-2 and 3-3). The high water requirements for operating natural gas and nuclear power plants stem primarily from cooling [35, 52].

It is estimated that 159.6 megajoule (MJ) of energy is required per kg of H_2 is needed for producing hydrogen via SMR [45] while up to 58.3 kWh per kg of H_2 is needed for electrolysis at 100% load [47]; energy inputs for SMR are in both heat and electricity forms while electrolysis only requires electricity-based inputs. Using the median values from [36], these energy requirements equate to an additional 0 to 1,556 L of water per kg H_2 depending on the specific hydrogen production pathway (Table 3-1). Generally, water consumption is an order of magnitude lower when using only renewable energy versus other energy sources [53].

In regions where desalination of seawater might be of more interest [39], an additional 0.5 kWh per kg of H_2 would be needed for powering reverse osmosis activities [43]. The associated water requirements for hydrogen with co-located energy generation, thus, can increase water requirements by 0 to 13.3 L of water per kg H_2 depending on the specific production pathway, source water, and energy source for gaseous hydrogen production with evaporative cooling (Table 3-1).

3.1.3. Manufacturing

As noted above, there are different types of equipment required for hydrogen production, with SMRs used for blue hydrogen while electrolysers are used for pink and green hydrogen. Of the different types of electrolysers, alkaline and proton exchange membranes are the most mature and widely installed of the technologies ([37, 39]). Although some insights are available regarding the geographic distribution and costs of the different manufacturing capacities of these technologies ([43, 54, 55]), little is known about the amount of water that is required to manufacture the SMR and electrolyser equipment. Consultations with hydrogen SMEs revealed that these water values might be considered proprietary [47]. The complex and fragmented nature of the current manufacturing of these technologies furthers complicates the collection of relevant insights [39].

3.2. Wind

3.2.1. Background

In wind energy operations, turbines convert the kinetic energy of wind into mechanical energy and subsequently to electrical energy using a generator [56]. The relatively low levelized cost as well as high efficiency throughout its lifespan makes wind energy an attractive option as a low-carbon electricity generator [57]. The three primary components of a turbine are the tower, nacelle (which houses the generator and other electronics), and blades (Figure 3-2); these components account for 46, 44, and 10% of the total mass of the turbine respectively [58]. Wind turbines can be installed on dry land (onshore) or offshore on the sea or in freshwater [59]. As of 2021, 774.2 gigawatt (GW) of onshore and 54.2 GW of offshore wind capacity have been installed globally [60]. Wind installations continue to increase, especially in China and other parts of Asia [61]. While most countries obtain less than 5% of their electricity from wind, a few nations (mainly in Europe) are generating more than 30% of their power from wind energy [62].

3.2.2. Electricity production

Although there are significant uncertainties in estimates, the overall life cycle water requirements for wind production tend to be orders of magnitude lower than fossil-based energy generation [64, 36]. The water estimates for wind range from 0.0038 to 0.234 L per kWh for onshore wind [65, 66]. Offshore wind, however, generally has higher estimates, with values ranging from 0.188 to 8.25 L per kWh [31, 32, 64]. Generally, there is some agreement that most of the water used is withdrawn as opposed to consumed [67, 68].

For wind operations, in particular, the literature consistently notes that relatively low amounts of water are needed. For example, one set of estimates from a global meta-analysis indicates that the median value of water needed for wind operations is 0 L/kWh [36]. Another summary report states some differences between onshore and offshore water requirements, ranging from 1-2 gallons per MWh (onshore) to 1-9 gallons per MWh (offshore) [69]. The higher amounts of water

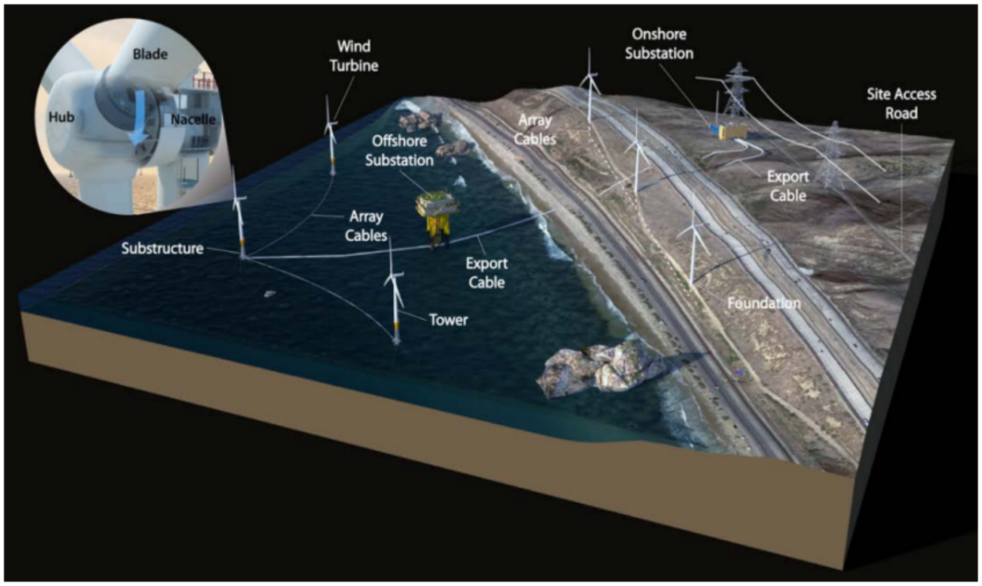

Figure 3-2 The primary components of a wind plant are a tower, blades, and nacelle. The larger system involves a network of cables to transmit energy generated from the wind plant. Source: [63]

for offshore turbines likely reflects other maintenance needs related to the crew transfer vessel. However, conversion of these amounts to L per kWh shows that these requirements are still very small (Table 3-2).

Table 3-2 Water withdrawal for wind power production.

	Value	Units	Source	Notes
Direct water input for wind plant operations				
	0-0.01	L/kWh	[36, 35, 69]	
Cradle-to-gate (direct and indirect) water input for manufacturing				
2 MW turbine	1.8×10^8	L/turbine	[70]	water use
2 MW turbine	10.3×10^6	L/turbine	[31]	consumption
2 MW network connection	1.5×10^5	L/turbine	[31]	consumption
Blade	$5.8 \times 10^5 - 1.9 \times 10^6$	L/blade	[71]	consumption

3.2.3. Manufacturing

A majority of water use associated with wind energy generation is linked to manufacturing of wind turbines and their parts [64, 67, 70, 72]. Case studies (of 1 to 11 turbines) have found that the nacelle, tower, and blades (compared to other components such as transportation and installation) require the most water [73]. A cradle-to-gate assessment revealed that 0.046 L per kWh of water is used to manufacture a 2 MW Grid-Streamer turbine [70]. These values equate to 1.8×10^8 L per turbine assuming a total of 3.8×10^6 kWh for the full 20-year life of a turbine

[70]. While 2 MW is comparable to the average capacity of commerically installed wind turbines in the United States [74], it is not clear whether these overall water use numbers for a Grid-Streamer turbine are reflective of all wind turbines, especially those produced in recent years. Water consumption estimates indicate that 10.3×10^6 L of water is needed per turbine [31]. Though a straightforward comparison of onshore and offshore wind energy water use could not be found, the manufacturing of the floating platform approximately doubles the water use for floating turbines as the platform's footprint is approximately equal to the turbine itself [64].

A study on water use in manufacturing of 20 different wind turbine blades (from three different manufacturers) provides a range of 578 to 1,897 tonnes of water (equivalent to 5.8 to 190 $\times 10^5$ L per blade) to produce three blades [71]. In one blade, the addition of carbon fiber spars increased water use by 9.1% [71]; carbon fiber spars are used in larger turbines onshore and increasingly in offshore blades as well. At the generator-level (which is part of the nacelle), three different common types contribute less than 0.0001 L per kWh to the water depletion over their life cycles [75]. However, the total amount of water needed for manufacturing a generator is not available. There are estimates that an additional 1.5×10^5 L is needed to support manufacturing of network-related components to support broader information and workforce communications from the wind plant [31].

Further breakdown of turbine components by sector shows that mining and quarrying and petroleum, chemical, and non-metallic mineral products account for approximately 40% of water use [73]. It is assumed that these water requirements associated with mining are captured in the cradle-to-gate values presented in (Table 3-2). Although LCI data contain both direct and indirect water inputs [31], it is not clear if the other sources use a similar methodology.

3.3. Solar

3.3.1. Background

Solar energy involves harnessing the sun's electromagnetic radiation to more useful forms of energy, such as heat or electricity. This review focuses on the latter applications, specifically through use of photovoltaics (PV), which has accounted for almost all of the increases in solar-related investments in recent years [76]. PV technologies involve using a series of semiconductors that absorb light from the sun and transfer that energy to electrons. Energy from the electrons is then extracted by the PV system in the form of electrical current for use as needed. To boost the power of the PV system, semiconductors in a PV cell are strung together into solar modules, which are then used to assemble PV systems. The popularity of PV systems stems from two factors: 1) the ability to scale systems with ease and 2) significant potential for solar energy generation around the world. PV systems can be relatively small (e.g., 1 kW) for local use (e.g., residential rooftops) to larger, multi-GW systems for utility-scale production that are integrated into the local electricity grid [77]. Although higher performance has been observed with floating-based systems, the vast majority of PV installations have been on land [78]. The potential for solar energy generation is also well-distributed around the world, especially in the southern latitudes [39]. This has led to significant regional investments, with some regions increasing their installed capacity from 3x (e.g., in North America) to 11x (in Africa) in less than

two decades [9]. A majority (85-90%) of PV-related manufacturing (wafers, cells, and modules), however, is concentrated in only one location, China [79].

3.3.2. Electricity Production

Overall life cycle estimates for PV range from 0.004 to 7.2 L per kWh, with the higher values being driven by water dependencies for electricity-related inputs [36, 31, 80, 81, 82]. There are also some differences in water requirements based on the composition of the panel, with mono- and poly-silicon crystalline panels having lower life water requirements than amorphous silicon panels [28]. Generally, the median value for total water withdrawals for PV is 0.36 L per kWh, with approximately 30% of the withdrawn water being consumed [80, 82]. A significant amount of the water is needed for the construction of utility-scale PV power plants [80].

Water requirements during the actual operations of a solar PV plant are generally low [36]. For solar PV plant operations, most of the water is used for panel washing and dust suppression or some panel cooling [82, 83]. Current water withdrawal estimates for operations range from 0 to 1.2 L per kWh [36]. The lower estimates in the meta-analysis review could reflect regional variations (e.g., estimates of water consumption are 0.02 L per kWh in China, 0.1 L per kWh in Egypt, and up to 1.2 L per kWh in the United States [36]) as well as increasing use of rainfall and other water-free (e.g., brush) cleaning techniques [84, 85]. Table 3-3 contains a summary of these ranges. In some studies, the relatively low amount of water needed for PV operations (compared to fossil-based generation sources) has led to this phase being excluded from calculations altogether (e.g., [86]).

Table 3-3 Water withdrawal requirements for land-based photovoltaics systems. Electricity requirements for manufacturing indicate those for major manufacturers. Conversion of electricity requirements to water used natural gas, nuclear, solar, and wind-related operational needs for water.

	Value	Units	Source
Direct water input for PV plant operations			
Panel washing, dust suppression	0 -1.2	L/kWh	[36]
Direct water input for PV manufacturing			
Mono-silicon production	5,004	L/kg	[87]
Multi-silicon production	943	L/kg	[87]
Wafer manufacturing	57	L/m^2	[87]
Cell manufacturing	172-251	L/m^2	[87]
Wafer manufacturing	1.3	L/wafer	[88]
Cell manufacturing	3.4	L/cell	[88]
Module manufacturing	41.8	L/module	[88]
Indirect water input for PV manufacturing			
Wafer manufacturing	$0 - 7.7 \times 10^4$	L/wafer	[88, 36]
Cell manufacturing	$0 - 1.9 \times 10^4$	L/cell	[88, 36]
Module manufacturing	$0 - 4.8 \times 10^5$	L/module	[88, 36]

3.3.3. Manufacturing

Manufacturing of PV spans multiple components, including manufacturing of polysilicon, wafers, cells, and modules (Figure 3-3). Each of these activities has an underlying water requirement that ranges from 1.3 L to over 5,000 L per each unit (Table 3-3). Water during manufacturing is needed as a feedstock for generation of ultrapure water as well as for cooling-related needs [85, 87]. A life cycle analysis of PV manufacturing notes that for a kg of mono-silicon production, 4 L of deionized water and almost 5,000 L of tap water is needed for larger cooling needs [87]. Generally, ingot casting and silicon refining are considered the most water demanding steps of the overall PV manufacturing process [89].

Multi-silicon crystalline production requires 943 L of water per kg of silicon [87], but at least half of the water is likely consumed [90]. Another 57 L of direct water input is needed per square meter (m^2) for wafer manufacturing and 172-251 L needed per m^2 of cell production [87]. These numbers are generally consistent with the values provided by other researchers [90] and those provided in the LCI [31]. The LCI estimates for cradle-to-gate range from 7,885 to 9,706 L depending on the specific PV component and type of silicon [31]; the slightly higher estimates likely reflect the inclusion of mineral extraction in the LCI database. There are also some variations between different types of PV modules, with thin-film PV (e.g., Cadmium-Tellurium based cells, Figure 3-3) generally consuming half the amount of water during manufacturing relative to crystalline silicon PV [82].

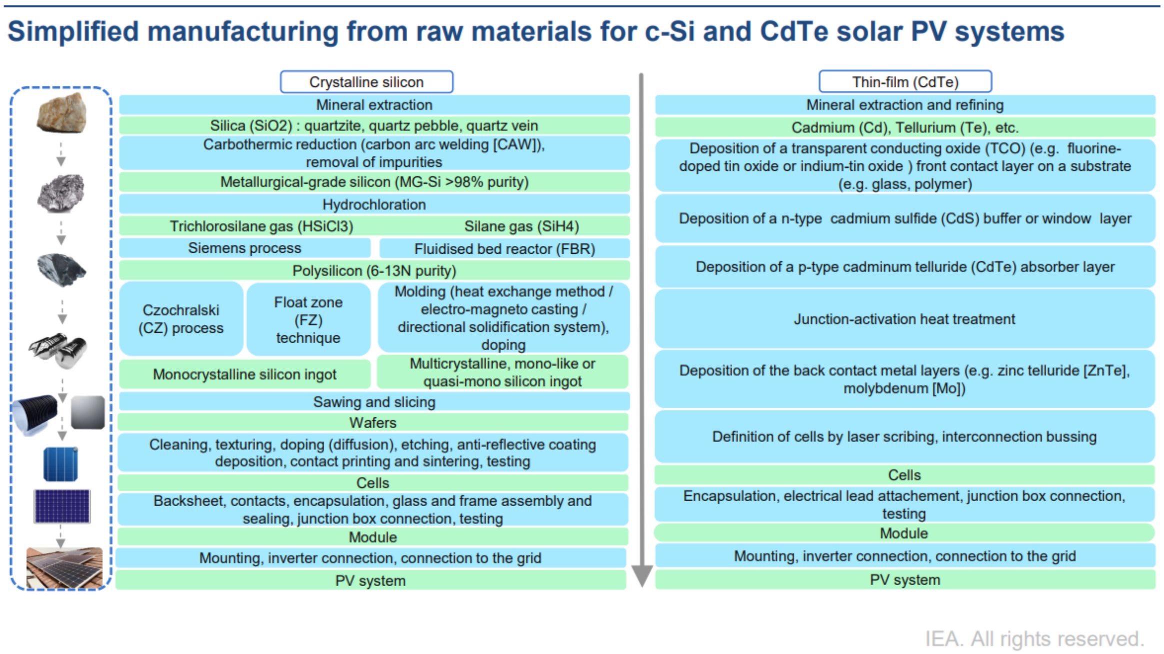

Figure 3-3 Manufacturing of photovoltaics involves a number of activities that are dependent on the specific module technology. Source: [91]

For silicon-based PV systems, associated electricity inputs for manufacturing is generally much lower for wafers (1.3 - 2.9 kWh) and cells (0.3 - 0.7 kWh) than for modules (18 kWh); lower end

of the range reflect advanced practice technologies while the higher end of ranges reflect standard major manufacturer practices [88]. Using the median water use requirements for nuclear, natural gas, solar, and wind (from [36]) can translate these electricity values into additional (indirect) water inputs needed for manufacturing, which range from 0 (for wind-based energy inputs) to 5.8×10^5 (for nuclear energy-based inputs). These estimates, of course, would vary depending on the specific mix of energy generation sources in a region, which can lead to varying water impacts for PV. For example, one estimate indicates that more water quality impacts (e.g., eutrophication) are expected in China due to higher use of biogas and hard coal (relative to Germany) [92]. These researchers also estimate a greater water use for PV manufacturing is expected in Germany relative to China [92]. However, the latter could be an artifact of inconsistencies in tracking since others have indicated that water use for PV manufacturing is relatively high in China due to the low level of water recycling in the country [90].

To address water scarcity concerns, manufacturers in some regions (e.g., Capital Solar in the Silicon Valley of the United States) have started to find ways to not only reduce water, but also overall energy needed to manufacture semiconductors and other parts of the solar panels [93]. Similar attention is being paid by other manufacturers to reduce water amounts needed for PV manufacturing. For example, First Solar has worked to improve water efficiencies and increase water recycling through installation of evaporators [94] while Canadian Solar has standardized water inflow rates and reduced cross-contamination of chemicals as a part of their water conservation strategies [95]. However, water numbers from these practices are not reflected in current peer-reviewed literature sources. Instead, there is a prevalence of older data sources (often stemming from 1990s and 2010s) for PV-related water requirements in the current literature [96].

3.4. Battery Technologies

3.4.1. Background

The capacity to efficiently store electricity for later use is a crucial factor in realizing energy transitions. Energy storage can take on many different forms (e.g., electro-chemical, kinetic, and thermal) and can provide varying amounts of storage capacity [97, 98]. For this report, the focus is on lithium-ion batteries (Li-B), which have a range of applications including both electric vehicles (EVs) and electric grid operations. In Li-Bs, energy is stored and released as the electrolyte transports positively charged lithium ions between the anode and cathode through a separator [99]. Interest in Li-B spans various countries including China, the United States, and Europe. In 2021, China accounted for 79% of all Li-B produced worldwide, with the U.S., Hungary, and Poland contributing smaller percentages at 6.2%, 4%, and 3.1% respectively [100]. China dominates production in almost every stage of the global battery supply chain, containing 67% of battery cell production, 80% of the cathode production, and over 90% of anode production [101]. However, it is projected that Germany will emerge as the second largest producer of Li-Bs worldwide, encompassing approximately 11% of the total global production capacity by 2025 [100].

3.4.2. Operations

Water requirements for Li-B during their life cycle assessments can vary depending on the geographic location of raw minerals and materials, the type of cathode used, and the specific boundary conditions used for LCAs [102, 103, 104]. Li-Bs do not require direct water input during operations, but there are indirect water requirements stemming from the energy needed to charge and manage batteries [105]. Use of Li-B in both EV and grid operations require an energy input for the charging process while electric grid operations require additional inputs for thermal management [106].

To calculate the equivalent water requirements for charging Li-Bs, the global median water withdrawals for nuclear, wind, PV, and natural gas are used [36]. For EV operations, a total of 32.8 MWh are needed to charge an EV over its operational life span, assuming a total distance of 200,000 kilometers (km)[2] and average electricity consumption of 16.4 kWh per 100 km [108]. This electricity requirement translates to 0 to 8.8×10^3 L of water per kWh needed for operations depending on the electricity generation technology (Table 3-4).

For grid operations, these numbers are augmented by the amount of water needed to support air conditioning or cooling of the battery energy storage systems. Approximately 35 kW of energy input is needed per MWh of battery storage for thermal management of the battery storage system [109]. So, assuming a 20-year lifespan of a Li-B with 24 hour cycling [110], a total of 6.1×10^6 kWh of energy is required for the thermal cooling of a 1 MW grid-integrated energy storage system. This equates to an additional 0 to 1.6×10^5 L of water per kWh needed as a indirect input to support thermal management of batteries used for grid-integrated systems (Table 3-4). These estimates are heavily dependent on the size of the cooling system needed, which can vary depending on the local climate conditions. For example, a 1 MW battery system in Alaska may only need an 8 kilovolt-amp system for cooling while a smaller, 730 kW battery system in Iowa may require 30 kilovolt-amps for cooling [111]. Depending on the type of cooling system used, direct water inputs may also be required for the grid-integrated battery system. For example, a 300 MW battery plant in California, USA reported that they use 124,800 gallons of water per minute, which is equivalent to 94.3 L/kWh (Table 3-4).

3.4.3. Manufacturing

The actual production of the Li-B requires no water (i.e., often done in dry rooms with less than 10% humidity to maintain an anhydrous environment) [113]. However, the larger manufacturing facility has significant water requirements associated with cooling, raw material preparation, washing and filtering, and wastewater treatment [114]. For instance, a Samsung battery facility in Hungary uses approximately 27,000 m^3 of industrial and drinking water daily [115]. Another estimate indicates that a 100-GW Hungarian battery factory would require 800 MW of energy and roughly 1,000 m^3 of water per hour [116]. Like any other industrial process, the source water is treated and purified to a particular quality needed for production [114]. Throughout the treatment process, there is reject water, which can be recovered and recycled or returned to the initial intake.

[2] This is the average distance traveled by private cars in China [107]

Table 3-4 Water requirements for Li-B cell production. NMC111, NMC622, and NMC811 reflect different mineral compositions for cathodes.

	Value	Units	Source	Notes
Indirect water withdrawals for battery charging (EV and grid)				
Nuclear	8.8×10^5	L/unit EV	[36, 106]	life span of 200,000 km EV
Natural gas	7.4×10^4	L/unit EV	[36, 106]	life span of 200,000 km EV
Wind/PV	$0 - 1.6 \times 10^3$	L/unit EV	[36, 106]	life span of 200,000 km EV
Direct water withdrawals for thermal management for grid-connected batteries				
	94.3	L/kWh	[112]	300 MW system
Indirect water withdrawals for thermal management for grid-integrated batteries				
Nuclear	1.6×10^5	L/kWh	[36, 109]	life span 20-year Li-B
Natural gas	1.4×10^3	L/kWh	[36, 109]	life span 20-year Li-B
Wind/PV	0 - 301	L/kWh	[36, 109]	life span 20-year Li-B
Direct and indirect water consumption for battery cell manufacturing				
NMC622/NMC811	411 - 456	L/kWh	[103]	includes mineral extraction
NMC111/NMC811	802 - 1221	L/kg	[31]	includes mineral extraction

Depending on the production plant, there may be a cooling system attached to the process, which requires its own water consumption considerations specific to the cooling type process (Figure 3-4). Water disposal management also occurs during the manufacturing of the battery itself, through raw material preparation, washing and filtering, and calcination of lithium [114].

The direct and indirect water requirements for battery cell manufacturing are included in Table 3-4 for Nickel Manganese Cobalt (NMC), which is one of the most commonly used lithium-ion chemistries for cathodes in Li-Bs [113]. A cradle-to-gate life cycle assessment found that the direct and indirect water consumption for manufacturing NMC batteries can range between 411 and 456 L per kWh [103] or 800 to 1,220 L per kg [31], with some small variations depending on the mineral compositions (Table 3-4). The water consumption is primarily driven by variations in water use during mineral extraction processes [103]. In these studies, the indirect water consumption for the energy requirements for manufacturing components and battery assembly is estimated using energy mixes in either China [31] or Chile [103]. However, these values could vary depending on the local energy generation mixes.

Water efficiency opportunities for batteries stem from cooling- and cleaning-related technologies. The presence of heavy metals in water resulting from battery production is also more prevalent than commonly realized [117]. However, most LCAs for batteries do not take into account all of the water needed to properly treat waste water, leaving water withdrawn and consumed the same for Li-B [118]. Consultations with an SME indicated that water-specific summary for batteries are not likely to be present in most industry reports since the primary drivers of battery-related discussions are energy and costs [113]. However, some battery manufacturing plants (e.g., with Tesla's plant in Berlin, Germany) have faced public opposition due to water quantity and quality concerns, which has resulted in more attention being given to this resource in some regions [119].

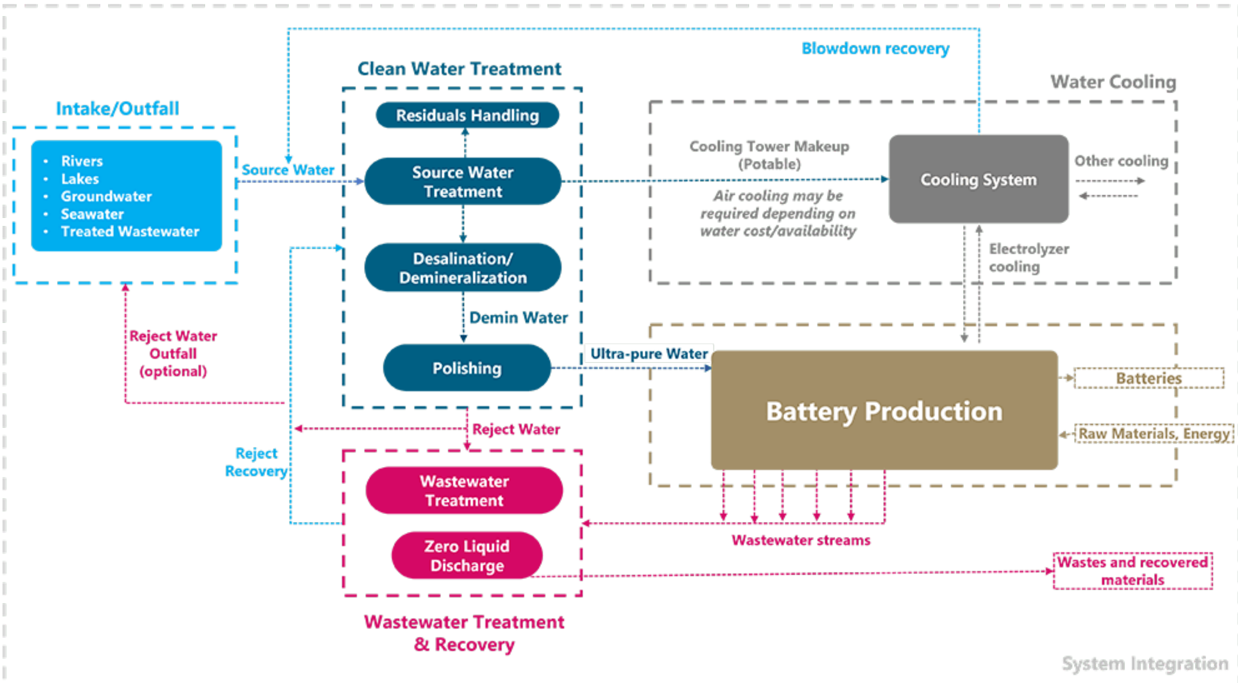

Figure 3-4 Water and wastewater management components that go into battery production. The larger bounding box (i.e., grey dotted line) reflects the larger integrated system associated with production of batteries. Source: [114]

3.5. Minerals

3.5.1. Background

Critical minerals play an important role in clean energy transitions since the associated technologies rely more heavily on these minerals compared to traditional fossil fuel-based energy sources [120]. The extraction of critical minerals is posing a limitation on the pace and extent of energy transitions due to the scale of amounts needed. Part of this challenge stems from securing access to water resources needed for the extraction and processing of these raw materials [120]. For this review, we concentrate on five of the minerals that have been identified as being critical to the energy supply chain [34]: lithium, nickel, copper, cobalt, and graphite. Figure 3-5 shows the breakdown of the top three producing countries for the selected minerals.

Distinct from requirements associated with technology-specific manufacturing, water is required throughout all stages of mineral extraction and on-site processing. For example, water is needed during extraction (hydraulic or solution mining); transportation of material and waste products (in the form of slurries and suspensions); mineral refinement (grinding, leaching, density separation, metallurgy); and ancillary processes for environmental controls (dust suppression, cooling) [121]. The amount of water resources required for mineral development depends on many factors including resource type (e.g., ore versus brine), required purity, extraction method, processing technologies, and local water availability.

Various types of adaptations have been proposed to reduce the water footprint of mining,

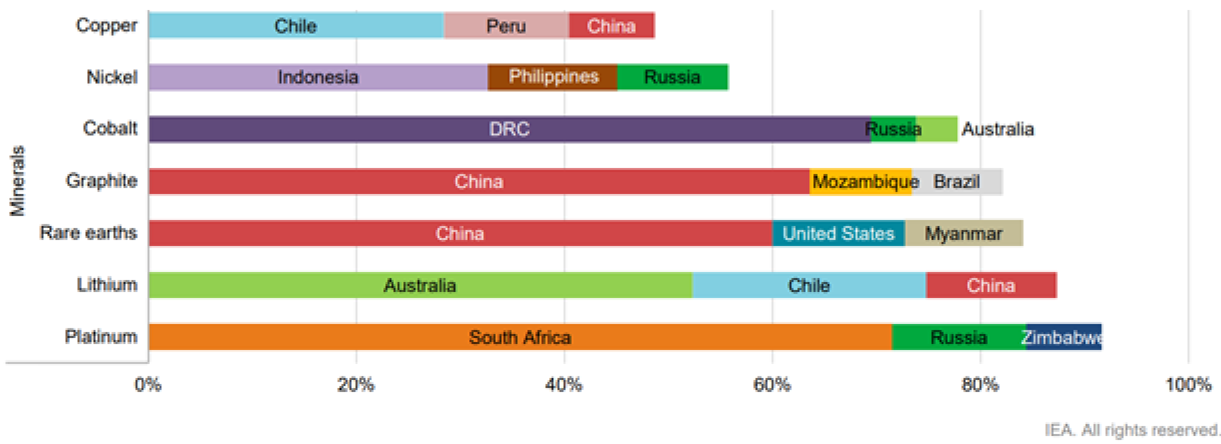

Figure 3-5 Share of top three countries (2019) involved in processing of selected minerals. DRC is the Democractic Republic of Congo. Source: [120]

including use of alternate, lower quality water sources (e.g., treated wastewater or recycled processed water); using dry processing techniques; and reusing water from mine dewatering activities [120]. For example, most of the saline groundwater (80%) used in the United States is for mining activities [122]. Unfortunately, water use in mining can be highly variable and very few published reports capture associated coefficients (sometimes due to proprietary concerns) [123]. Below, we briefly describe the water-related details that were available in the reviewed literature for each of five selected minerals. Water withdrawal numbers were not available in reviewed literature, so this section focuses only on water consumption for the five selected minerals (Table 3-5).

3.5.2. Lithium

Of the four energy transition technologies reviewed, lithium is used only for the production of lithium-ion batteries [120]. The increasing demand for batteries is expected to cascade into an increase in Li demand of almost 90% over the next two decades [120]. Both ore-based and brine-based extraction methods are used to process Li into purities needed for battery manufacturing inputs. Australia and China dominate markets for Li ores, while Li brine products are typically sourced in Chile [124]. Regardless of origin, over 70% of Li facilities are located in areas of high water stress where significant competition exists between users [79].

Lithium can be sourced from either ores (spodumene and lepidolite being the most common) or from brine deposits (typically found in salt flats or aquifers). Ore-based Li extraction typically involves a crushing-milling-benefication process to separate the lithium, which requires a very high amount of material volume [121, 125]. The cradle-to-gate water use for ore-based methods (that mine spodumene) is 2,330 L to produce 1 kg lithium carbonate (Li_2CO_3) [125] (Table 3-5). For ore-based processes, the majority of the water use is related to the upstream production of input material at the leaching step (57.6%) and electricity (25.6%), making refinement the highest water consumption phase [125]. Other activities, like milling and benefication, also drive water requirements for ore-based processing [121].

Table 3-5 Water consumption from cradle-to-gate of selected critical minerals. These values include direct and indirect water inputs during material extraction, transport, and refining, ending at input consumer facility.

Mineral	Value	Units	Source	Notes
Lithium	770-840	L/kg Li_2CO_3	[31, 120, 125]	brine-based; fresh inputs
	2,330	L/kg Li_2CO_3	[125]	ore-based
Copper	0.5 - 3.5	L/kg ore	[126, 127, 121]	copper sulfide
	0.37 - 0.87	L/kg ore	[127]	copper oxide
	53 - 259	L/kg Cu	[120, 31]	
Nickel	87	L/kg ore	[121]	nickel sulfide
	415	L/kg ore	[121]	nickel laterite
	10 - 1,481	L/kg Ni	[120, 31, 124]	
Cobalt	59-8,386	L/kg Co	[31, 120, 128, 124]	
Graphite	9.9	L/kg Gr	[31, 120]	battery-grade

Although ore-based operations recover higher material yields (∼3.7% Li) relative to brine-based operations (0.06-0.15%) [129], more Li is obtained using brine-based methods (60%) that involve extracting Li-rich groundwater and evaporating it in ponds [102, 130]. The overall water consumption for brine-based methods per kg of Li is 770 L [120]. Although the LCI database does not specify the exact processes used for lithium, the values presented in the LCI (840 L) are similar to those presented in other brine-based studies [31, 125] (Table 3-5). The amount of water evaporated can range (depending on the deposit) from 100-800 m^3 per tonne of Li_2CO_3 (equivalent to 100-800 L of water per kg) and is thus, causing concern about the long-term supply and sustainability of this process [131].

An additional factor influencing water scarcity concerns for Li processing is the increased reliance on groundwater sources, often due to the lack of surface water availability near inland brine lakes [102]. Thus, during processing activities, two different aquifers are exploited: Li-rich brine and fresh, groundwater. All groundwater used to pump out the brine is considered in the water consumption values summarized in Table 3-5. These values do not include the actual water of the brine itself since the high concentration of total dissolved solids (TDS) in these sources are often assumed to be unsuitable for human use [103]. For example, TDS values in Salar de Atacama, Chile are approximately 350 grams per L in Salar de Atacama, which is 10x greater than the TDS of seawater [103]. Some estimates indicate that less water may be needed to produce lithium hydroxide (80 to 469 L per kg) [124]. However, lithium carbonates are generally preferred as inputs for Li-B manufacturing since they require less processing to generate battery-grade Li.

Long-term environmental impacts, such as degradation and drawdown of scarce local water sources continue to be a concern for lithium mining activities, with acidification potential reported as being significantly higher in ore-based activities than brine-based ones [129, 125]. Some stages in resource development chains allow for recapture of water previously consumed for transport, processing, or ancillary purposes. By some accounts, new operations can increase recycling such that new water is only needed for less than 1% of total water budgets [125].

However, recycled water cannot eliminate the need for new water because of successive contamination and enrichment. Furthermore, it is not clear from the literature if and how many mining operations are implementing water conservation strategies.

3.5.3. Copper

Copper (Cu) is an important mineral for all electricity-related technologies, with large amounts involved with offshore and onshore wind production and solar PV [120]. Copper is expected to remain the largest contributor (70%) for energy-related needs (larger than iron ore and bauxite combined), with total demands expected to increase by over 40% by 2040 [79]. Global copper production reached 21 million metric tons in 2021 [132]. The major countries involved with copper extraction are Chile, Peru, and China, with the latter dominating processing activities for this mineral [120]. A decrease in ore quality has been observed in recent decades (e.g., up to 30% in Chile), which has contributed to increasing water resources required per unit and raising further concerns about water-related tensions [133]. Similar to lithium, a number of copper facilities (39%) are located in areas of moderate to high water stress that can be influenced by competition between water users [79].

Copper can be extracted from either copper sulfides or copper oxides, each of which is processed differently [127]. Processing of copper sulfides (which accounts for 80% of current copper production today) involves pyrometallurgy while processing of copper oxides involves hydrometallurgy. Pyrometallurgy activities involves smelting of the material, which consists of crushing and grinding the rock and then using flotation to extract concentrates for smelting [127]. In contrast, copper oxides subject to hydrometallurgy are exposed to acids in a heap leach, with the resulting solution sent to solvent extraction and electro-winning to extract the minerals [79, 127]. In the pyrometallurgy processes, water is used for grinding and flotation activities while in hydrometallurgy processes, water is used for the leaching heaps and other ponds used for storing material [127].

In general, pyrometallurgy requires more water than hydrometallurgy-based processes. A 2012 US Geological Survey study noted that approximately 1.5 to 3.5 tons of water per ton of ore (equivalent to 1.5 to 3.5 L of water per kg of ore) is required to process copper sulfides through a crush-grind-flotation-concetrate circuit [126, 127]. Other studies note that only 0.5-0.7 L of water per kg of ore is needed for copper sulfides, even when indirect inputs from electricity are included [121, 79]. A majority of these requirements are associated with flotation (tailings, slurries) and makeup water requirements for entrainment, evaporation, seepage, and other losses [126, 127]. In contrast, freshwater consumption for a hydrometallurgy-based plant is only 200 gallons per ton of ore (equivalent to 0.83 L per kg of ore) [127]. If recirculation is maximized, leaks are avoided, and evaporation is reduced, the water requirements can be reduced to about 90 gallons/ton of material (equivalent to 0.37 L per kg of ore), as has been shown to be possible in some plants in Chile [127] (Table 3-5). From an end product perspective, water consumption values associated with copper have been estimated to be approximately 53 L [120] whereas the LCI database estimates 196 to 259 L of water per kg of copper is needed, depending on whether the copper is used in cathodes or anodes respectively [31] (Table 3-5).

3.5.4. Nickel

Of the four energy transition technologies, nickel (Ni) is critical for lithium-ion batteries and wind turbine manufacturing [120]; some future scenarios project that nickel may also be needed for PV [63]. The presence of nickel increases the energy density and storage capacity in Li-Bs at a lower cost while nickel-based alloys increase the strength and rust resistance of wind turbines so they can operate without fracturing [134]. In 2022, the global production of nickel from mines was estimated to reach a total of 3.3 million metric tons [135]. The major countries involved with nickel production are Indonesia, the Philippines, and Russia [120]. Current estimates indicate an increase in 60-70% for nickel production is expected in the next 20 years [120].

Nickel is mined from ores, mainly from nickel sulfide and nickel laterite deposits. These ores have distinct characteristics and require different processing methods to extract and refine nickel. Sulfide deposits are typically extracted through underground mining methods, akin to the techniques employed for copper, but some deposits are mined using open pits. On the other hand, the extraction of nickel-rich strata from laterites primarily involves heavy machinery and requires the removal of large boulders and waste material [136]. In recent years, the demand for battery-grade nickel has shifted extraction activities from sulfide resources to laterite resources. However, the production of nickel from laterites requires more energy compared to sulfide-based resources [120].

Typically, sulfide ores are processed using pyrometallurgy whereas laterite ores are mostly procssed using both pyrometallurgy (35%) and hydrometallurgy (65%) [128]. Since more water is needed for pyrometallurgy than hydrometallurgy, the amount of water needed to process these ores vary from 79 m^3 water per ton of sulfide ore (or 87 L per kg of ore) to 376.6 m^3 water per ton of laterite ore (or 415 L per kg of ore) [121] (Table 3-5). Although processing of sulfide ores for nickel requires multiple cleaning steps to drain acid from the waste material [128, 136], the difference in water requirements for the two ores is driven by the water needed for leaching activities for laterites [121]. These estimates take into account indirect water requirements for electricity, which vary from 11% for sulfide ores to 2% for laterite ores [121]. The variations in processing activities are reflected in the large range in water amounts required per kg of processed copper, which span from approximately 10 L [124] to 1,481 L [31] (Table 3-5).

3.5.5. Cobalt

Cobalt (Co) is mainly used to help ensure high power density and long life spans in the manufacturing of cathodes for Li-Bs, although there may also be some uses in wind production [63, 120]. The top three countries extracting cobalt are the Democratic Republic of the Congo (DRC), Russia, and Australia, with the DRC covering 70% of the market [137, 120]. Cobalt is frequently found in conjunction with other metals such as copper (∼55%), and nickel (∼35%) and is often extracted as a by-product of these metals [138]. Thus, similar processes of pyrometallurgy and hydrometallurgy (such as crushing and grinding of ore to froth flotation) often apply across Co and the other minerals [128]. In addition, vapor-metallurgy, which involves passing gases through the ore to help deposit minerals, may also be used for cobalt extraction

methods [128]. Generally, water requirements for Co are driven by leaching-related needs as well as mitigation of particle emissions associated with blasting activities [128].

Overall water consumption estimates for the production of cobalt range from 75 L per kg of Co per the IEA [120] to 8,386 L within the LCI database [31]. An alternate LCA analysis indicated that only 59 L of water is depleted to produce 1 kg of Co, with only 4% of this amount being required for energy and blasting-related activities [128] (Table 3-5). The large variations in amounts of water needed for Co may be driven by differences in regional practices, with one corporation (Glencore) reporting that their Canadian mines use 211 L per kg of Co while their DRC mines use 950 L per kg of Co [124]. The high values from LCI could also be driven by the specific energy source, such as hydropower [31]. Unfortunately, specific breakdown of water requirements across the different ore types or metallurgical processes were not available in the current literature.

3.5.6. Graphite

Graphite (Gr) is a critical mineral for the production of Li-Bs, specifically in anodes. Due to its high energy density and relatively low-cost, graphite makes up 28% of a typical Li-B by weight [139]. The global production of graphite was 1.3 million metric tons in 2022, with China as the top producer (90%), followed by Mozambique and Brazil [120, 140]. Graphite can be found in different forms, including amorphous graphite and flake graphite; the latter is typically more suitable for Li-B applications [141]. Projections note that demand for graphite could grow from 140 kilotons in 2020 to 3,500 kilotons in 2040 [120]. However, some estimate that the higher electron capacity in silicon (10x that of graphite) could temper this growth [120]. There has also been a rise in the production of synthetic or artifical graphite (specifically for Li-Bs). Although artificial graphite has almost no impurities, it is more energy-intensive, costly, and can have more environmental polution [141]. To date, LCA studies for artificial graphite have not considered water input requirements (e.g., [142]), thus, only values for natural graphite are presented below.

There are various methods for processing natural graphite, including froth flotation and gravity separation [141]. For the first process, mined graphite ores go through a crushing and grinding process to generate a fine powder. This powder is then mixed with water and chemicals to create a frothy mixture that undergoes flotation to separate graphite from the other mineral content [141]. The continuous addition of water makes flotation methods more water-intensive than other graphite concentration methods, such as gravity separation. Gravity separation processes typically involve creation of a slurry as well, but generally rely on material densities to separate graphite from other minerals, thus requiring less water than froth-based techniques [141].

The overall cradle-to-gate water consumption for graphite is estimated to be 9.93 L of water per kg of graphite according to both IEA and LCI [31, 120]. Few resources discuss water consumption for graphite, with most researchers relying on LCA databases, such as LCI [143]. However, one empirically-grounded study that consulted a Chinese manufacturer noted that approximately 22 m^3 of water is needed during the flotation process and another 25 m^3 of water is needed during the purification process [143]. However, the functional units of these numbers in

the study change between processes (from graphite concentrate to spherical purified graphite), making it hard to reconcile these values into consistent units. The study does note that almost all of the water ($\sim$99%) used during graphite processing is returned as wastewater [143]. Associated electricity inputs for processing a tonne of material are also included in the study: 8.7 kWh (for mining); 506 kWh (for flotation); 2,100 kWh (for spheronization); 305 kWh (for purification); and 4,550 kWh (for coating) [143]. Thus, coating and spheronization activities are the most energy-intensive of the natural graphite processing activities.

Although water requirements for graphite are relatively low compared to other minerals (Table 3-5), recycling of graphite can help offset water-related costs associated with processing of raw materials [144]. However, the recycling activities can also have interdependent water requirements [144].

4. DISCUSSION AND CONCLUSIONS

4.1. Synthesis of Findings

The literature indicates that of the four technologies, hydrogen will require the most water as a direct input during the operations stage. The use of battery technologies does not generally require direct water inputs as they need an anhydrous environment for operations. However, as noted above, water may be required for supporting cooling for grid-integrated battery systems. Estimates for direct water inputs for PV and wind are both consistently low, leading some researchers to exclude these phases from calculations altogether (e.g., [86, 145]). In contrast, the large range of values for hydrogen reflect the diversity of production pathways (SMRs and electrolysers) as well as associated energy inputs (natural gas, nuclear energy, wind, and PV) (Figure 4-1). Approximately 64% of the total direct water used in hydrogen operations is consumed [47].

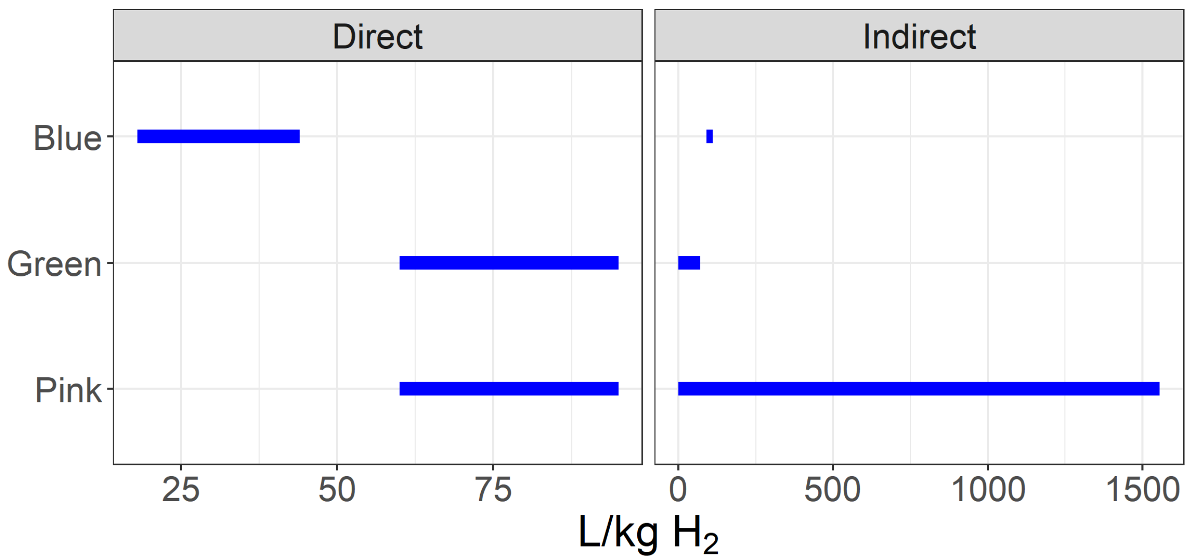

Figure 4-1 Direct and indirect water withdrawals for hydrogen production.

Indirect water requirements only apply for battery and hydrogen technologies, since both require energy inputs for operations. The indirect water withdrawal values range from 0 (for wind-based energy generation) to 3,485 liters of water for hydrogen (Table 3-1) to thousands of liters of water for generating the electricity needed to charge batteries and for supporting thermal management for grid-connected systems (Table 3-4). The specific values depend on the energy generation mix being used to generate the needed electricity for these operations.

Details about manufacturing, on the other hand, are relatively sparse for all four technologies. For example, discussions with SMEs revealed that water data associated with hydrogen production might be considered proprietary, while tracking and reporting water data for battery manufacturing is generally not considered a priority [47, 113]. There were limited numbers for wind-related manufacturing as well, with only one peer-reviewed source providing total water use

requirements (of 180 million liters of water) for a cradle-to-gate assessment (Table 3-2). Comparison of this estimate to values provided in LCI database indicates that approximately 5% of the water used in wind manufacturing is consumed [31].

More details were available in the literature about PV-related manufacturing. Generally, more direct water inputs are needed for manufacturing an individual module relative to the individual cells and wafers (Table 3-3). Assuming that there are 17 grams of silicon per wafer, each cell consists of one wafer, and 72 cells per module [146, 147], we can convert the individual unit numbers into water requirements associated with a single PV module as a functional unit (Figure 4-2). This visual clarifies that polysilicon-related requirements are the largest driver of water needs for PV module manufacturing. There are also electricity requirements associated with manufacturing PV components. Similar to the approach used for batteries, translating these electricity values into water equivalents results in 0 to 480,000 L of additional water needed indirectly (depending on the energy source) to support PV manufacturing activities (Table 3-3).

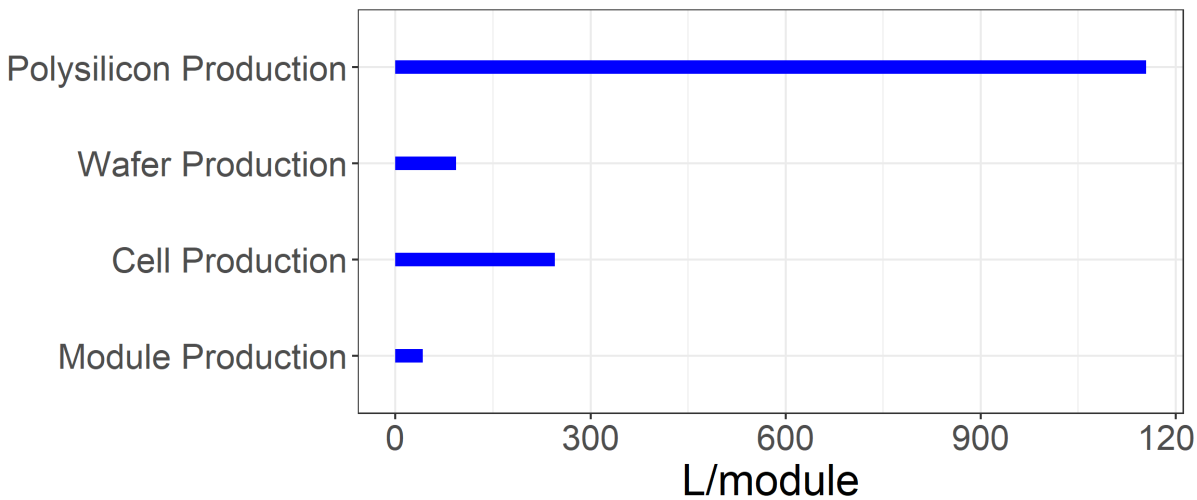

Figure 4-2 Direct water withdrawals for manufacturing a single PV module, including associated polysilicon, wafers, and cells.

Finally, water requirements for five critical minerals were assessed. These minerals are mostly used in Li-B production, but copper and nickel are also used in renewable energy generation (Figure 2-1). Unlike operations and manufacturing activities, which sometimes contained total withdrawals, literature on water for mining was restricted to water consumption-related amounts. Generally, processing of cobalt required more water than any of the other minerals while processing of natural graphite required the least (Figure 4-3). Although they are often found in association with each other, water resource depletion estimates are marginally lower for copper than for nickel and cobalt [128]. While lack of comprehensive data precludes direct comparisons, hard-rock sources tended to require more water than brine-based methods (Table 3-5).

Resource scarcity concerns have led some of the energy technology sectors to pursue water adaptation practices. These range from using different sources of water to cooling-related improvements (Table 4-1). Unfortunately, specific numbers of reductions are captured in (few)

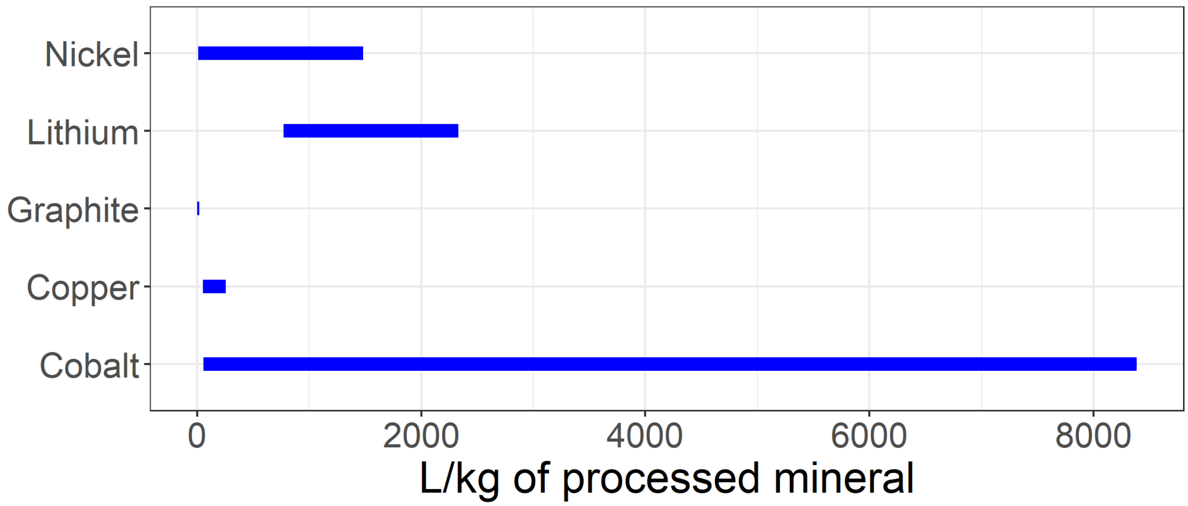

Figure 4-3 Cradle-to-gate water consumption for mining activities

industry-specific reports and thus, it is hard to ascertain how widespread these adaptations are across regions and within each sector.

Table 4-1 Adaptation strategies being pursued for water scarcity and conservation-related motivations within each of the four energy technologies.

Sector	Adaptations
Hydrogen	Saline water sources Water-efficient cooling technologies Water reuse
Wind	-
PV	Water recycling Reduction of cross-contamination
Li-B	Water-efficient cooling technologies Streamlining cleaning activities
Mining	Water reuse Use of lower quality water Dry processing

4.2. Limitations

There are multiple limitations to this literature review, mostly stemming from the lack of consistency in functional units analyzed and lack of statistically-representative water data for energy-related activities. As noted in prior sections, many of the original data sources did not use consistent units, which made it hard to include all available information in a consistent format. Furthermore, the available values were often dated and provided values specific to only one or two regions of the world (mostly outside China) [96]. Additionally, it was not always clear if the values presented in the literature reflected a notional activity from that region or were derived

from empirical observations. These data quality-related challenges are not unique to this report and have been recognized by other researchers in this domain as well [148, 124, 89]. Thus, it is highly likely that the values present in the current literature do not reflect the actual amount of water being currently used for operations, manufacturing, and mining associated with the four energy technologies reviewed. A summary of the observed data issues is captured in Table 4-2 along with an indication of the team's relative confidence in the representative nature of presented data. Given these limitations, it is probably more appropriate to look at presented values as relative magnitudes versus absolute numbers.

Table 4-2 Water data quality-related observed during the literature review.

Sector	Relative Confidence	Data Observations
Hydrogen	Low	Inconsistent operational values in published sources No details for manufacturing-related needs
Wind	Medium	Consistently low values for operational needs Sparse details regarding manufacturing requirements
PV	Medium	Consistently low values for operational needs Industry best practices do not align with peer-reviewed literature
Li-B	Medium-Low	No details for manufacturing-related needs Indirect water needs derived based on electricity-equivalents
Mining	Low	Poor resolution for various stages of mining Outdated data sources

Finally, this review only considered certain activities associated with the four energy technologies. For example, the blue, green, and pink production pathways for hydrogen could be mixed together such that multiple energy sources are used together to produce hydrogen [44]. Technological innovations, such as mining natural hydrogen [149], use of auto-thermal reformers (which use a similar process as SMRs, but vary in how heat is injected into the process to improve overall carbon capture efficiency) [150, 151], and capturing water through steam recovery may also influence the amount of energy and water required for hydrogen operations [152]. Recycling activities of the different technologies (which span specific minerals to modules [85, 87, 144]) were also not included in this initial assessment. Since water is required for many of the recycling processes, this area warrants further attention.

4.3. Future Work

In addition to addressing the limitations noted above, future work could also expand to consider the broader natural and human water systems influencing these technology roll-outs, such as variations in water availability over time, water quality, community acceptance, and region-specific priorities. More details about each of these possible directions are captured below.

Most of the numbers captured in the research, to date, look at the associated water requirements as a static value. However, varying precipitation patterns could influence the relative stress these

technology development activities face from local water resources. Furthermore, it is not uncommon for technology owners to adapt to water scarcity and variability [153], which would further alter the sensitivity between local water availability and actual impact to local production practices.

Water quality impacts from the manufacturing and mining of these technologies is also of concern for many. For example, freshwater toxicity (during site installations) and marine aquatic ecotoxicity (from manufacturing of nacelles and towers) have been a concern in wind manufacturing [64, 70, 154]. The latter concerns are likely to increase as additional investments are made in offshore wind generation. Although some waste-related management requirements are accounted for in current LCAs (e.g., [87]), degradation of water resources is generally overlooked in most technology assessments. This oversight is a significant concern, especially given increasing awareness of these water-related issues. As noted in the prior sections, public response to some of the water concerns has already started to influence citing and design of some of the manufacturing facilities [119]. On the mining side, freshwater ecotoxicity, water eutrophication (e.g., fish kills, toxic algae), and acidification are among the most publicized impacts of mineral development experienced by local communities [155]. Additional factors that can influence public buy-in include considerations for workforce development and cultural values [156]. For example, within the U.S. a significant portion of current mineral reserves (68%, 89%, 79% and 97% for cobalt, copper, lithium and nickel, respectively) are located within 35 miles of a Native American Reservation [133]. Reservation regions often have much longer permit cycles (16-20 year) compared to other countries (which can be as short as 4) [120]. Thus, inadequate accounting of communities priorities could influence social licenses to operate and ultimately, the roll-out of these technologies.

Finally, region-specific nuances are also worth taking into account for future work. By tailoring analyses to local practices, region-specific assessments could increase the accuracy of both water quantity and water quality impacts by accounting for specific technology operating conditions. For example, in Australia, the reliance on fossil fuels and limited water resources near ore-based lithium deposits has led to 60 fold increases in environmental impacts [125]. All of the available energy technologies in a region could also be integrated into a single assessment to identify further opportunities for adaptations and mitigations. Depending on the region, additional technologies (e.g., pumped storage hydropower [157, 158]) and activities (e.g., end uses of hydrology and mining of rare earth elements [65]) may also need to be taken into account. Regional assessments could also integrate community priorities and governance mechanisms (e.g., regulations and supply trade) that could influence water use and related adaptations. A number of techniques (ranging from mapping available water data [159] to mining newspaper content [160] and system dynamics models [161]) can be used to aggregate these diverse datasets into a singular platform for region-specific evaluations.

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